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Results from a Water-Čerenkov Array

The CYGNUS Collaboration

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Abstract

Five surface water-Čerenkov detectors (pools), running in coincidence with the CYGNUS extensive air shower array, are described. Preliminary results on the timing response and the estimated angular resolution of the pools are presented. Based on comparisons between the pools and the scintillator array, the angular resolution of the pools is estimated to be $\sim 0.5°$, consistent with Monte Carlo predictions. Pool trigger rates and photoelectron (pe) lateral distributions are also presented.

Introduction

The sensitivity to point sources of ultra high energy γ rays can be improved by decreasing the energy threshold and/or enhancing the angular resolution of air shower arrays. Water-Čerenkov detectors used in conjunction with a traditional air shower array can do both, because a water-Čerenkov detector is sensitive over its entire surface to all electromagnetic components of an air shower. The CYGNUS collaboration has built five water-Čerenkov detectors to develop the technology and to improve the angular resolution of the CYGNUS extensive air shower array.

The Pool Experiment

The CYGNUS air shower array located in Los Alamos, NM, has been described elsewhere (see Alexandreas *et al.* 1992). The CYGNUS I array consists of 108 scintillator detectors spread out over an area of 22,000 m^2. The angular resolution of the CYGNUS I array is $\sim 0.7°$ (as determined by the cosmic ray shadowing by the Sun and the Moon (see Alexandreas *et al.* 1991a)). The median energy of a detected cosmic ray is ~ 100 TeV. The current trigger rate is about 3.5 Hz.

The pools are located within the CYGNUS I air shower array, arranged in roughly a cross shape with 60 m arms. Each pool is 7.5 m in diameter and ~ 3 m deep, containing 7 fast (< 2.3 ns RMS jitter for a single pe) 10" Burle photomultiplier tubes (PMTs). Six PMTs are arranged in a hexagon surrounding a central PMT on the bottom of the pool. Above the photocathode there is ~ 2 m of water which provides a medium for the production of Čerenkov light by the particles in air showers. The pools are read out on every CYGNUS event. 99% of the CYGNUS-I events produce a signal in at least 1 pool.

In order to reconstruct the direction of the initiating primary particle from the pool data, the timing in each pool photomultiplier tube with 1 or more photoelectrons is first corrected for shower curvature and sampling using the core reconstucted by the CYGNUS array. Like the timing in the CYGNUS-I air shower array, the correction is linearly dependent on the core distance. The dependence of the correction on pulse height in the pool PMTs, however, is logarithmic, which is somewhat different from the dependence on pulse height in CYGNUS-I (see Biller 1992). The pool information is used to find the arrival direction of the air shower by fitting to a shower plane. The differences between the predicted arrival times of the fitted shower planes and the actual times measured in 1 PMT (timing residuals) are shown in Figure 1. Superimposed on this figure is a Gaussian curve with a $\sigma = 2.1$ ns. If one requires ≥ 10 pool PMTs to be hit (at least 1 pe each), and these PMTs are distributed among 3 to 5 pools, then $\sim 75\%$ of the CYGNUS-I events can be reconstructed using only the pool information.

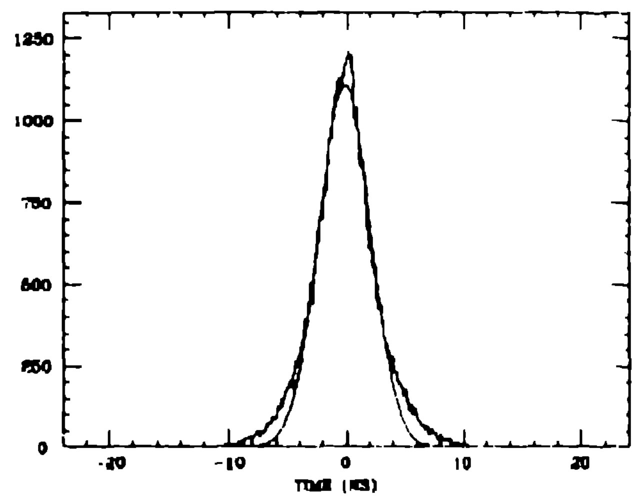

Figure 1. Time Residual of a pool photomultiplier tube with respect to the Pool fitted shower plane from any direction. The RMS of the times is ~ 2.2 ns. Also shown is a Gaussian with $\sigma = 2.1$ ns.

ANGULAR RESOLUTION

Using an event by event comparison between the directions reconstructed by the pools alone and by CYGNUS-I alone, the angular resolution using 3 or more pools is estimated. Figure 2 shows a histogram of the space angle differences between the reconstructed arrival directions using only the pool information versus the reconstructed arrival directions using only the CYGNUS-I array. This distribution is fit with a symmetric two-dimensional Gaussian curve, with an additional exponential tail. The tail represents $\sim 10\%$ of the events in the plot. The standard deviation of the Gaussian part of the distribution is 0.8°. If the angular resolution of the CYGNUS-I is characterized by a two dimensional Gaussian, then the standard deviation of that distribution for these events is $\sim 0.65^\circ$. The CYGNUS-I resolution is somewhat better than quoted above because those showers that trigger CYGNUS-I and at least 10 PMTs distributed among 3 or more pools are of a somewhat higher energy. Because the two arrays independently reconstruct the shower's arrival direction

$$\sigma^2_\theta = \sigma^2_{CYG-I} + \sigma^2_{pools}$$

where σ_θ is the standard deviation of the Gaussian part of the space angle difference histogram. Then the resolution of the 3 pools for these cuts is $\sim 0.5^\circ$. This estimate is in agreement with Monte Carlo results (see Alexandreas *et al.* 1991b).

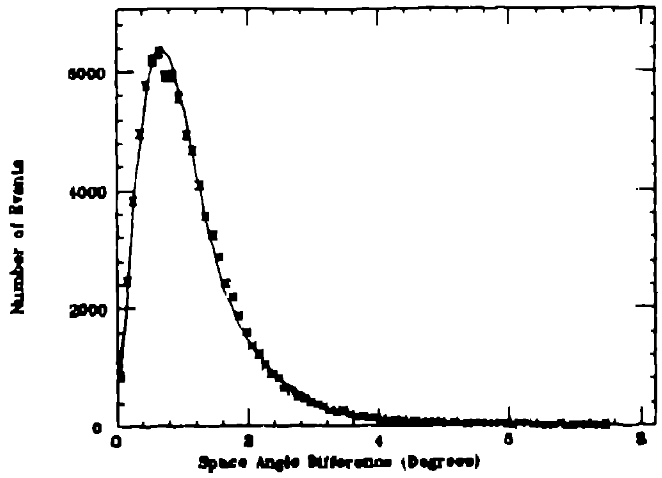

Figure 2: Space Angle Difference between the independently reconstructed arrival directions of the two arrays, and the fitted Gaussian (σ_θ=0.8°) with exponential tail

ENERGY THRESHOLD STUDIES

The trigger rate for various coincidence requirements was determined for the array of water-Čerenkov detectors. A pool was triggered if the summed pulse height of its PMTs was $\geq$2 pes. Three sets of data were taken: (a) 3-5 pools triggered in time coincidence, (b) 4-5 pools triggered in time coincidence and (c) all 5 pools triggered in time coincidence. For each data set, the trigger rates were measured for a minimum number of PMTs in each triggered pool; each PMT was required to have at least 1 pe. Figure 3 shows the measured rates for each of these three data sets as a function of the minimum number of PMTs per pool with $\geq$1 pe. The maximum number of photomultiplier tubes shown on the plot is only 6, not 7, because several of the pools had a missing photomultiplier tube at the time this measurement was performed. When at least 3 pools were required to have at least 3 photomultiplier tubes with at least 1 pe in each PMT, the trigger rate was ~50 Hz, an order of magnitude larger than the current CYGNUS-I rate.

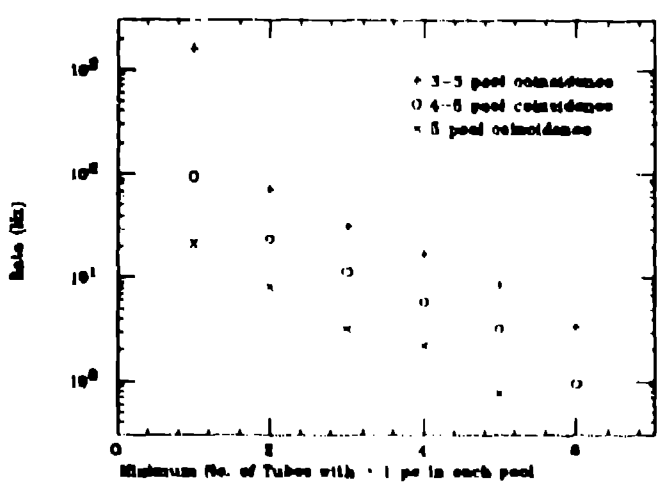

Figure 3: Pool Trigger rates requiring at least 3, 4 and 5 pool in time coincidence, with at least 1-6 hit photomultiplier tubes per pool. When 3 pools were required with at least 3 hit photomultiplier tubes (>1 pe each), the rate is 55 Hz.

Figure 4 shows the photoelectron lateral distribution in the pool photomultiplier tubes as a function of core distance, where the density was averaged over many shower sizes and ages (and the core fell inside the CYGNUS array). Also shown is the NKG particle density as a function of core distance for the average shower of size 16,000 particles, and age of 1.6. The NKG density function is a few orders of magnitude smaller than the photoelectron density because the function describes particle density in the air shower, not the photoelectron density measured by the pool PMTs. These two plots have the same general shape, although the photoelectron distribution flattens out near $R_{core}=0$ because of the uncertainties in the core locations. In general, this plot shows that the pools sample the air shower quite well, even at large core distances.

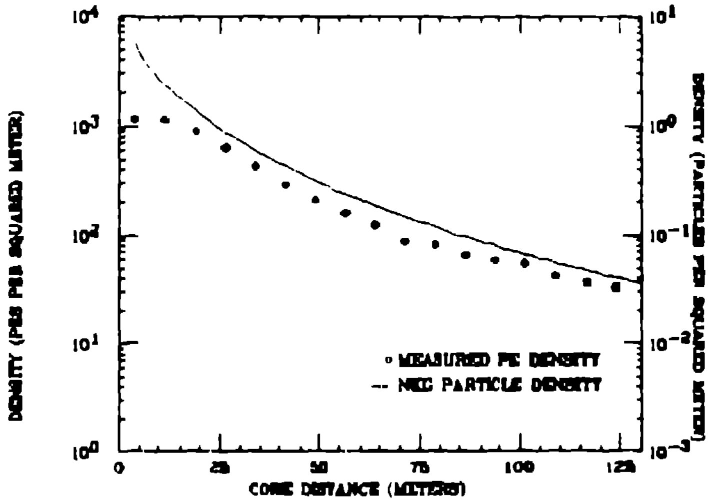

Figure 4: The photoelectron density as a function of core distance as measured by the pool PMTs (left scale), and the NKG particle density (right scale) for an average shower (16,000 particles and 1.6 age).

ACKNOWLEDGMENTS

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